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Cleaning Excavated Soil Using Extraction Agents
A State-of-the-Art Review

Foster Wheeler Enviresponse, Inc., Livingston, NJ

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CLEANING EXCAVATED SOIL USING EXTRACTION AGENTS:

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16. ABSTRACT This report presents a state-of-the-art review of soil washing technologies and their applicability to Superfund sites in the United States. The review includes Superfund site soil and contamination characteristics; as well as soil cleaning technologies, their principles of operation, and process parameters. The technical feasibility of using soil washing technologies at Superfund sites in the United States is accessed.

Contaminants are classified as volatile, hydrophilic, or hydrophobic organics; PCBs; heavy metals; or radioactive material. Soils are classified as either sand, silt, clay, or waste fill.

Three generic types of extractive treatments are identified for cleaning excavated soils: water washing augmented with a basic or surfactant agent to remove organics, and water washing with an acidic or chelating agent to remove organics and heavy metals; organics-solvent washing to remove hydrophobic organics and PCBs; and air or steam stripping to remove volatile organics.

Although extraction of organics and toxic metal contaminants from excavated sandy/silty soil that is low in clay and humus content has been successfully demonstrated at several pilot-plant test facilities, extraction from clay and humus soil fractions is more complicated.

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FOREWORD

Today's rapidly developing and changing technologies, and industrial products and practices frequently carry with them the increased generation of materials that, if improperly dealt with, can threaten both public health and the environment. The U.S. Environmental Protection Agency is charged by Congress with protecting the Nation's land, air, and water resources. Under a mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural systems to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts, and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing, and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, programs, and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication is one of the products of that research and provides a vital communication link between the researcher and the user community.

This report reviews technologies that have potential for cleaning excavated soils by use of extraction agents. Areas for further research and development are identified to aid in developing potential treatment technologies for volume reduction of Superfund soils prior to land disposal.

For further information, please contact the Superfund Technology Demonstration Division of the Risk Reduction Engineering Laboratory.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

In response to the RCRA Hazardous and Solid Waste Amendments of 1984 prohibiting the continued land disposal of untreated hazardous wastes, the U.S. Environmental Protection Agency (EPA) has instituted a research and development program for new technologies to treat RCRA and Superfund wastes. As part of this research program, technologies applicable to cleaning excavated soils were reviewed.

This report presents a state-of-the-art review of soil washing technologies and their applicability to Superfund sites in the United States. The review includes Superfund site soil and contamination characteristics; as well as soil cleaning technologies, their principles of operation, and process parameters. The technical feasibility of using soil washing technologies at Superfund sites in the United States is assessed.

Contaminants are classified as volatile, hydrophilic, or hydrophobic organics; PCBs; heavy metals; or radioactive material. Soils are classified as either sand, silt, clay, or waste fill.

Three generic types of extractive treatments are identified for cleaning excavated soils: water washing augmented with a basic or surfactant agent to remove organics, and water washing with an acidic or chelating agent to remove organics and heavy metals; organics-solvent washing to remove hydrophobic organics and PCBs; and air or steam stripping to remove volatile organics.

Although extraction of organics and toxic metal contaminants from excavated sandy/silty soil that is low in clay and humus content has been successfully demonstrated at several pilot-plant test facilities, extraction from clay and humus soil fractions is more complicated.

More pilot-scale testing must be conducted to support any statement on the environmental and economic practicability of extraction technologies at sites in the United States.

This report was submitted in partial fulfillment of Contract No. 68-03-3255 by Enviresponse, Inc. under the sponsorship of the U.S. Environmental Protection Agency.

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ABBREVIATIONS

APOC	Ammonium pyrrolidine carbodithiate
atm	Atmosphere
B.E.S.T.	Basic Extraction Sludge Treatment
°C	Degrees Celsius
CHC	Chlorinated hydrocarbons
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act (Superfund), 42 U.S.C.A. Chapter 9601 et seq.
cm	Centimeter
CFR	Code of Federal Regulations
DTPA	Diethylenetriamine pentaacetic acid
EDTA	Ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
EP Tox	Extraction Procedure Toxicity (40 CFR 260.20, 260.21)
ERT	Emergency Response Team
°F	Degrees Fahrenheit
FS	Feasibility Study
g	Gram
hr	Hour
HSWA	Hazardous and Solid Waste Amendment (to RCRA)
kg	Kilogram
kw	Kilowatt
L	Liter
M	Molar
m^3	Cubic meters
mg	Milligram
mm	Millimeter
MM	Million
NPL	National Priority List (established under CERCLA, 42 U.S.C.A. Chapter 9601 et seq, Section 105(B)
NTA	Nitrilotriacetic Acid
PCB	Polychlorinated biphenyls
PNA, PAH,	Polynuclear aromatic hydrocarbons
ppm	Parts per million
psi	Pounds per square inch
RAMP	Remedial Action Master Plan
RCRA	Resource Conservation and Recovery Act (42 U.S.C.A. Chapter 9601 et seq)
RI	Remedial Investigation
SARA	Superfund Amendments and Reauthorization Act of 1986 (Public Law 99-499)
TEA	Triethylamine
USATHAMA	U.S. Army Toxic and Hazardous Materials Agency
um	Micron
VOC	Volatile organic compounds

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SECTION 1

INTRODUCTION

BACKGROUND

Under the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA), clean up activities at hazardous waste sites must reduce the toxicity, mobility, and volume of hazardous substances. The 1984 amendment to the Resource Conservation and Recovery Act (RCRA), the Hazardous and Solid Wastes Amendment (HSWA), was created in large part in response to citizen concerns that existing methods of hazardous waste disposal, particularly land disposal, were not safe [1].

The 1984 RCRA amendments prohibit the land disposal of untreated hazardous waste unless the Environmental Protection Agency (EPA) finds that there will be "no migration of hazardous constituent for as long as the wastes remain hazardous [1]." The land ban provisions of the 1984 RCRA amendments have given considerable impetus to developing more economic and more effective means of treating waste. EPA is now sponsoring research on new treatment technologies to destroy, detoxify, or incinerate hazardous waste; on ways to recover and reuse hazardous waste; and on methods to decrease the volume of hazardous waste requiring treatment or disposal [1]. On-site treatment technologies that remove or decrease contaminant levels may achieve a more positive control than containment techniques. Off-site disposal in landfills probably will be allowed in the future, but only when no treatment technology is available, because transportation of a hazardous waste creates opportunities for spills and accidents. In addition, as landfill disposal becomes more expensive and as hazardous waste transportation is more stringently regulated, on-site waste treatment technologies will become more desirable--if they are technologically demonstrated, environmentally safe, and economical.

ON-SITE SOIL TREATMENT

In response to the RCRA Amendment of 1984 which prohibits the continued land disposal of selected groups of untreated hazardous waste in the U.S., the EPA has instituted research and development programs for new treatment technologies for RCRA and Superfund wastes.

One of the research areas initiated by the EPA is cleaning excavated contaminated soil by extraction agents. Cleaning (washing) excavated soils holds promise for being applicable to all contaminants.

SOIL CLEANING FOR SAFE ONSITE REDEPOSIT

Soil cleaning employing extraction agents consists of soil excavation, above-ground onsite treatment, isolation and removal or destruction of the contaminant, and redeposit of the cleaned soil. Each technique used to separate the contaminant from the soil requires an extraction agent--a liquid, gas, chemical additive, or a combination of agents. The agent must mobilize the contaminant, which is chemically or physically attached to the soil particles. Because of some complex interactions between contaminants and certain soil fractions (clay and humus), further research and development work is needed.

As a first step, this report reviews the technologies that may be applicable for cleaning (washing) excavated soil. The purpose is to examine and evaluate physical separation and extraction technologies in the context of their applicability to soil cleaning. Specifically, this report:

1. surveys the contaminants (by type and concentration) and soil (by type and quantity) at the various NPL* sites to define the most frequently occurring problems at these sites,

2. reviews the extractive treatment technologies that have potential for cleaning the contaminants from soils, and

3. recommends areas for future research.

As of March 1987 a total of 951 sites are either on or proposed for inclusion on the NPL (40 CFR 300 Appendix B).

Section 2 of this report contains conclusions and recommendations for further research and development efforts in this area.

A manual search of the EPA files containing data on NPL sites in New York, New Jersey, and Puerto Rico was performed to identify the most frequently occurring problems. Section 3 presents the results of the survey.

Reviews of the extractive treatment technology show that there are three generic types of extraction processes for cleaning contaminated soils:

1. Water Washing with Extraction Agents;

   - Surfactants that promote the solubility of the contaminants in water;

   - Chelating additives that chemically react with metal ions and promote their solubility; and

   - Acid or alkaline solutions that mobilize, neutralize, or destroy the contaminant.

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*Section 105 of CERCLA required EPA to establish a list of hazardous waste sites (National Priority List).

2. Solvent Extraction of Organic Contaminants: An organic solvent dissolves and mobilizes the contaminant into the solvent.

3. Air Stripping of Volatile Organic Contaminants: Agents such as steam or air are applied. Heat, vacuum, or both increase the extraction rate.

These processes are reviewed in Section 4.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

The following conclusions and recommendations have emerged from this literature review of theoretical, bench-scale, and pilot-scale investigations on state-of-the-art technologies for the extraction of contaminants from soil.

- At 57 of the 82 sites surveyed in Region II, the contaminated soil is characterized as sand or silt. Total sandy/silty soil volume exceeds 10 million cubic meters. Pilot-scale tests conducted by TNO, Heijmans, HWZ Bodemsanering, BSN, and Ecotechniek show that sand or silt can be washed.

- Above-ground extraction of organics and heavy metals is feasible from sandy soil containing very low levels of clay and humus fractions.

- Above-ground extraction of organics and heavy metals from clay and humic soil fractions has not been demonstrated on the pilot-plant scale.

- Separation of the extractant from the soil and regeneration of the extractant have not been successfully demonstrated for clay soils.

- Contaminant extraction experience does provide enough information to support a decision on the technical feasibility of applying the technology at NPL sites.

- More applied pilot-scale testing must be conducted to support any statement on the environmental and economic practicability of extraction technologies.

- Experience with contaminant removal via water washing at the bench, pilot, and prototype scale supports the technology as it applies to sandy and silty soils. Its economic competitiveness with other remedial technologies such as incineration or fixation is implied at this time, but not fully quantified.

RECOMMENDATIONS

A program is needed that would include:

- Characterization of soil at NPL sites from a soil washing perspective. This would include particle size distribution, mineralogical observations, physical and chemical analyses, etc.

- Bench-scale testing program to establish the required processing configurations and operating conditions of the various wastewater treatment and regeneration subsystem options.

- Preliminary process design, sizing, and costing of a modular transportable pilot-plant system to determine process economics for comparison with incineration and other remedial technologies.

- Design, construction, and operation of a modular transportable pilot-scale unit to demonstrate applicability at selected NPL sites.

- Research and development efforts to broaden the application of washing soil containing high clay/humus fractions, if economically justified.

SECTION 3

PATTERNS OF CONTAMINATION AND SOIL COMPOSITION AT NPL SITES

A variety of contaminants and soil types can be found at Superfund sites. A survey of NPL site information files was conducted to determine the possible contaminants and soil types that are prevalent at these sites. Based on the survey, the various soil-contaminant type pairs were grouped to identify the pairs occurring with highest frequency. These pairs were matched with the potential extractive technologies that can be applied for cleaning soils, thus helping to determine which of the potential extractive technologies should be pursued further. The identification of the various soil-contaminant pairs is also essential in selecting and assessing agents used in the processes applicable to soil cleaning.

CLASSIFICATION OF CONTAMINANTS

The four most common multicompound concentration analyses performed on soil samples from NPL sites are those listed in 40CFR 136 [2] and the EPA Test Method for Evaluating Solid Waste (SW846) [3]. These are:

- Priority Pollutant Scan
- Priority Pollutants + 40
- Extraction Procedure Toxicity Test
- Partial scans of the above three (e.g., Volatile Organics Analysis)

These analyses are performed to determine the level of concentration of the priority pollutants and acutely hazardous substances that are listed in 40CFR 122.21, Appendix D [1] (see Appendix). These contaminants were grouped by the following four physical and chemical parameters that affect the ability of an extraction agent or process to mobilize them:

- water solubility;
- vapor pressure;
- octanol/water partition coefficient; and
- density.

These parameters were used to create separate lists of hydrophilic organic compounds, hydrophobic organic compounds, volatile organic compounds, and heavy metals (see Appendix). An additional contaminant classification, which is not addressed in this report, is radioactive materials. Definitions of the contaminant classifications addressed here are:

- "Volatile"--Having a vapor pressure greater than 5 mm of mercury at 25°C.
- "Hydrophilic"--Having a solubility in water over 10 g/L at 25°C.
- "Hydrophobic"--Possessing an octanol/water partition coefficient (K_{ow})* greater than 100.
- "Heavy metal"--Toxic metals and their compounds in ionic form.

This choice of definitions makes some highly soluble contaminants both hydrophilic and hydrophobic, while very slightly soluble materials are neither. Professional judgment was used to assign a single classification to each contaminant. Since K_{ow} data are not available for all of these materials, some of the characterizations were based on statements in the reference literature like "slightly soluble in water, very soluble in benzene."

Physical property information used to determine contaminant classification were obtained from:

- The CRC Handbook of Chemistry and Physics [4]
- The Chemical Engineering Handbook [5]
- The Condensed Chemical Dictionary [6]
- Sax's Dangerous Properties of Industrial Materials [7]
- The Handbook of Environmental Data for Organic Compounds [8]
- The Merck Index of Chemicals [9]
- The Chemical Profiles Appendix to the EPA Chemical Emergency Preparedness Program [10]

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*The octanol/water partition coefficient is defined as the ratio of a chemical's concentration in the octanol phase to its concentration in the water phase.

SOIL CLASSIFICATION

Attempts were made to characterize the soil present at each NPL site, but because detailed information on soil type was not available, gravel, sand, silt, clay, and waste fill were used as soil categories. The waste fill classification refers to dump sites where waste fill predominates and the type of associated soil is not defined. The municipal and chemical waste found in landfill sites are examples of waste fill. The humus or organic matter in the soil was noted when that identifying information was available.

It should be noted that soils are not homogenous and this classification system only assures that a soil classified as sand, silt, or clay will have a major fraction as sand, silt, or clay, respectively. For example, soils classified as sandy may also have silt or clay lenses in them.

SITE SURVEY PROCEDURES

The following information was obtained on each NPL site to evaluate applicability of potential extraction technologies:

- Name of site
- Types of contaminants present (see Appendix)
- Quantity of contaminated soil (including waste)
- Types of soil
- Average concentrations of contaminants

Originally, only NPL site information data bases maintained by EPA contractors were to be searched. The most likely data bases were identified by conferring with the personnel at CERCLA offices in Washington, D.C. The data bases were examined for the range of sites and the type and amount of information they provided. Data bases examined were:

- MITRE Data Base: Lists every NPL site and no other sites. The database contains information on contaminants present in groundwater, surface water, and air. There is no information on soil type, soil quantity,or contaminants in soil.
- Damage Incident Data Base: Lists most NPL sites and many others. Information on soil contaminants, contaminant concentrations, and quantity of contaminated soil is present, but there is no information on soil type.
- NPL Records of Decision Data Base: Lists 130 NPL sites. The data base consists of information on soil contaminants, contaminant concentrations, and quantity of contaminated soil; there is no information on soil type.

- CDM CERCLA Waste Type Data Base: Lists 59 NPL sites. Information encompasses soil contaminants and quantity of contaminated soil; no information is provided on soil type or contaminant concentrations.

The available electronic data bases did not contain all the information needed for this study. Therefore, EPA's files on as many NPL sites as possible were examined manually. A manual search of EPA Region II files of the NPL sites in New York, New Jersey, and Puerto Rico was performed.

Files on 194 sites were examined. The information on soil contamination was not adequate for assessment regarding soil washing in 56 of the files. Remedial/removal work was complete at 8 of the sites. Ground water (as opposed to soil) contamination was the important consideration at 35 sites, and no quantitative information on soil contamination was provided at ground water sites. Other types of nonsoil contamination were important at 13 sites. At the remaining sites, soil contamination data were adequate.

Most of the concentrations reported in these files were not computed, but are approximated averages of many individual data points listed in raw data tables at the back of Remedial Investigation (RI), Feasibility Study (FS), Remedial Action Master Plan (RAMP), Phase I, or Phase II reports. The approximate average was used because a simple arithmetic average would over-represent less-contaminated soil, which would be neither excavated nor processed. The type of soil was sometimes stated in great detail, as in an RI or FS. It was often only vaguely described (e.g., "This property is swampy."). Because the goal of the study was to obtain a soil contamination profile, precision was sacrificed in a few individual cases to increase the number of sites listed. The quality of the data was considered good enough for a profile study, but not good enough for definitive characterization of individual sites.

APPARENT PATTERNS OF SOIL AND CONTAMINANT OCCURRENCE

The 82 sites that had adequate soil contamination data were included in the data base for this study. If the Region II data are proportionally representative of the nation, then soil contamination at 402 of the 951 NPL sites can be assumed to have been characterized.

From data on soils and contaminants at 82 sites, 32 soil-contaminant type pairs were identified along with their frequencies of occurrence (Table 1). Many of the sites have more than one type of contaminant present; these sites appear under each applicable pair category in Table 1. Of the 176 occurrences identified in the search of the soil-contaminant type pairs as shown in Table 1, only three occur at significantly greater frequency than the remaining 29 pairs. These are hydrophobic volatile compounds, hydrophobic nonvolatile compounds, and heavy metals, all of them in sites with sandy soil. A typical site is about 40,000 cubic meters of sand with contaminant levels between 100 and 1,000 ppm. The occurrence of multiclass contamination at a site makes the requisite cleanup technology more complex. These are best assessed on a category-by-category basis.

TABLE 1. SUMMARY OF TOTAL SOIL VOLUME AND CONTAMINANT TYPES AT SURVEYED REGION II NPL SITES

Contaminant	Soil type									
	Sand		Silt		Clay		Waste		Total	
	No. of sites	Soil volume MM m^3	No. of sites	Soil volume MM m^3	No. of sites	Soil volume MM m^3	No. of sites	Soil volume MM m^3	No. of sites	Soil volume MM m^3
Hydrophilic volatile	12	0.73	3	0.24	4	0.03	7	14.83	26	15.83
Hydrophilic nonvolatile	4	0.51	1	0.61	1	0.01	2	0.91	8	2.04
Hydrophobic volatile	24	3.41	6	0.82	5	0.03	6	7.41	41	11.67
Hydrophobic nonvolatile	27	3.36	6	0.87	4	1.18	6	8.15	43	13.56
PCBs	4	0.47	1	0.01	2	1.15	1	0.05	8	1.68
Heavy Metal	20	6.42	8	1.18	3	0.43	10	17.2	41	25.23
Other Inorganic	2	0.05	1	0.01	-	-	2	4.59	5	4.65
Radioactive	3	0.21	1	0.03	1	0.02	--	0.06	5	0.32

SECTION 4

EXTRACTION TREATMENTS TO CLEAN SOIL

PROCESS CLASSIFICATIONS: AN OVERVIEW

Three primary types of extraction processes for cleaning contaminated soil are:

1. Water Washing with Extraction Agents:

   - Surfactants that promote the solubility of the contaminants in water;

   - Chelating additives that chemically react with metals and promote their solubility; and

   - Acid and/or alkaline solutions that mobilize, neutralize, or destroy the contaminant.

2. Solvent Extraction of Organic Contaminants: Organic solvent dissolves and mobilizes the contaminant into the solvent.

3. Air Stripping of Volatile Organic Contaminants: Agents such as steam or air are applied. Heat, vacuum, or both increase the extraction rate.

Water washing with extractive agents is applicable for cleaning nonvolatile hydrophilic and hydrophobic organics and heavy metals from soils. The solvent extraction processes show potential for cleaning nonvolatile hydrophilic and hydrophobic organics from soil. Air stripping processes are limited to cleaning soil of volatile organics.

These extraction treatment classifications encompass the information found in the literature pertinent to cleaning contaminated soil above ground. The relationship between extraction treatment and contaminant classifications is given in Table 2.

The information discussed in this section was obtained from the open literature. Water washing of soils with chelating agents and surfactants has undergone some recent bench-scale and pilot-scale testing. The use of acids and bases to remove metals and organics from contaminated soils has been successful. Soil washing with organic solvents has been tried on a limited

TABLE 2. EXTRACTION TREATMENT VS. CONTAMINANT CLASSIFICATION*

Extraction treatment	Contaminant classification					
	Hydrophilic organics	Hydrophobic organics	Volatile organics	Heavy metals	Other inorganics	Radioactive
Water washing						
Surfactants	X	X				
Chelation				X		
Acid and/or base	X	X		X	X	X
Solvent Extraction	X	X				
Stripping			X			

*Based on experimental treatment processes that have been proven effective on specific contaminants.

TABLE 2. EXTRACTION TREATMENT VS. CONTAMINANT CLASSIFICATION*

Extraction treatment	Contaminant classification					
	Hydrophilic organics	Hydrophobic organics	Volatile organics	Heavy metals	Other inorganics	Radioactive
Water washing						
Surfactants	X	X				
Chelation				X		
Acid and/or base	X	X		X	X	X
Solvent Extraction	X	X				
Stripping			X			

*Based on experimental treatment processes that have been proven effective on specific contaminants.

scale and for limited types of contaminated soil. Volatile organic stripping of soil with air has been utilized, whereby fresh air is induced or forced into the subsurface, and the vapor-laden air is withdrawn under vacuum from recovery wells.

Most of the soil cleaning processes involve intimate mixing of the extractant with soil, followed by solid/liquid separation where the cleaned soil is separated from the extractant fluid. The extractant is then cleaned of the contaminant and recycled as required. Table 3 shows the soil-contaminant type pairs along with their frequency of occurrence*. The type of potential extractant along with the applicable extractant and solid/liquid separation equipment for the soil-contaminant type pairs are also shown in Table 3. Some of the potential technologies that can be used to clean the extractant fluid as suggested by researchers and process developers are also shown in Table 3.

Cleaning soil contaminated with radioactive material was beyond the scope of this study and is not discussed.

In the next section, the generic extraction processes are described. For each of the processes the general process considerations, process description, related experience, and procedures for contaminant removal from soil are discussed. For the contaminants removal, the process parameters that will affect the process are identified. The specific soil cleaning experiences related to the contaminants removal are also presented.

WATER WASHING WITH EXTRACTION AGENTS

General Process Considerations

In water washing with extraction agents the washing solutions can be basic aqueous solutions (caustic, lime, slaked lime, or industrial alkali-based washing compounds); acidic aqueous solutions (sulfuric, hydrochloric, nitric, phosphoric, or carbonic acids); or solutions with surfactant or chelating agents. Hydrogen peroxide, sodium hypochlorite, and other oxidizing agents also are used to chemically change the contaminants. A strong (highly ionized) basic or surfactant solution can be used for some organic extraction, and strong (highly ionized) acidic or chelating agent solutions can be used for metal extraction. The surfactant and chelating solutions have a moderate (almost neutral) pH, making equipment metallurgy simpler, and operation safer. The successful development of a means to clean soil with surfactants and chelating agents is important because most soil at NPL sites is contaminated with organics and heavy metals.

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*Frequency of occurrence is based on 82 Region II NPL sites.

TABLE 3. SOIL-CONTAMINANT TECHNOLOGY MATRIX.

| | | |

Process Unit Description

Rulkens, et al., proposed a general block diagram of the equipment train that can be used to extract contaminants from excavated sandy soil (Figure 1) [11]. They also discuss commercially available types of equipment and processes for each unit operation. The excavated soil is pretreated by screening to remove large objects like pieces of wood, concrete, and drums; and hard clods of soil are reduced in size. These large objects are cleaned separately. The pretreated soil is mixed thoroughly with extraction agents, to strip the contaminant from the soil. This is followed by solid/liquid separation where the coarse fraction of the soil is separated. The extraction agent with contaminant and smaller soil particle (clay and fine silt) undergoes further solid-liquid separation where fine soil fractions are separated as much as possible. The extraction agent is cleaned and recycled. The separated soil fraction undergoes post-treatment where it is cleaned of any residual extraction fluid. Review of the literature reveals extractors and other equipment that can be used to treat excavated sandy, silt, clay, and humus soil. The equipment used is noted in the following section.

Related Experience

To date, several aqueous extraction systems for cleaning excavated contaminated soil have been demonstrated on a pilot scale. Demonstrating the operation of the equipment involves pretreatment, extraction of contaminated soil, and post-treatment of the extractant. The effective separation of the extractant from the soil, concentration of the contaminant, recycle of the regenerated extracting agent, and destruction of the contaminant have been demonstrated at a pilot level for very limited types of contaminated soil. Described below are the soil pretreatment/extraction experiences and post-treatment experiences.

Soil Pretreatment and Extraction Equipment Experience--

Limited experience with pilot-scale size equipment indicates that sandy soil probably can be processed. The processing of clays and silts has not been demonstrated and would involve developing unit processes to treat these fine colloidal soil fractions.

Netherland's Bromide Removal from Sand Study [12]--Reports published in November 1982 describe laboratory and pilot-plant-scale investigations undertaken in the Netherlands for removal of organic bromine compounds from soil. Sandy soil containing less than 10 percent clay and humus was cleaned by a 2:1 caustic solution (pH >11). The soil was pretreated by grinding in a low speed pen mill to reduce the size of soil clods. A 1-ton/hr inclined (30°) screw conveyor was used to extract the contaminant and separate the extractant from the soil. The soil and fresh extractant were fed into a hopper at the lower end of the screw. The spent extractant was removed as overflow from the hopper, and the clean soil was discharged from the screw top. The test information was used to engineer a future on-site treatment plant.

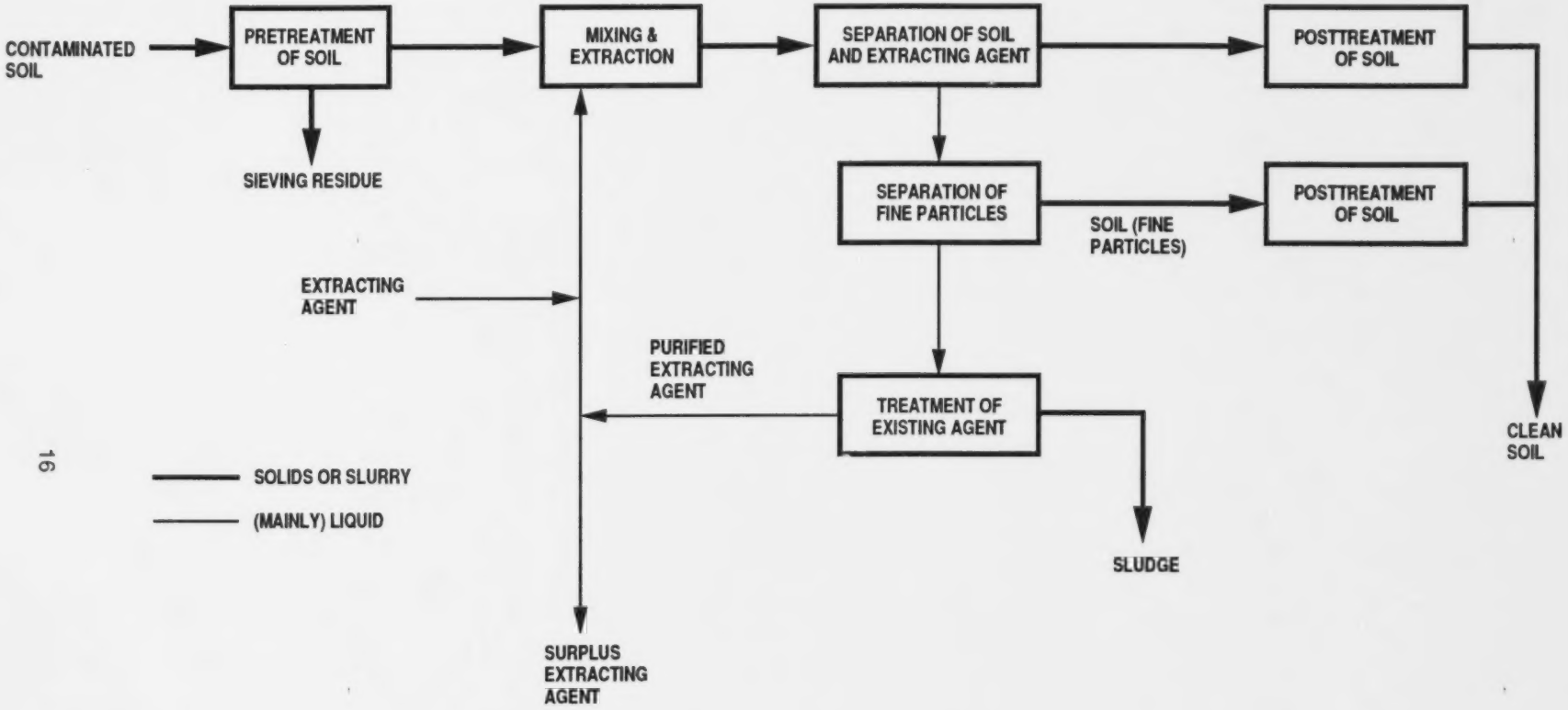

Figure 1. General block diagram for soil cleaning. Reprinted from Ruikens, W.H., J.W. Assink and W.S. Van Gemert. Project B: On-site Processing of Contaminated Soil. In: Contaminated Land Reclamation and Treatment, M.A. Smith,ed. Published in cooperation with NATO committee on the Challenges of Modern Society. Copyright © 1985 by Plenum Press, New York. Reprinted by permission of Plenum Press, New York.

Heijman's Milieutechniek's Extraction Cleaning of Heavy Metal and Cyanide from Soils [13]--Heijman's installation has been in operation since the spring of 1985 and has 10 to 15 ton/hr soil-handling capacity. The process begins with separating coarse (>10 mm) and fine materials by sieving and intensive mixing of soil with extracting agents and oxidizing chemicals. This is followed by coarse sand (>60 um), low-density materials (grass, coke, etc.), and silt separation by hydrocyclone, sieves, and tilt plate separators. The extracting agent is cleaned by flocculation and coagulation. The cleaned extracting agent is recycled. The process has potential for cleaning soil contaminated with cyanides, heavy metals, and water-immiscible and low-density hydrocarbons. Table 4 shows results of some of the runs of the Heijman process. The process is suitable for soils that contain less than 30 percent fine solids (<63 um) and humus-like compounds.

HWZ Bodemsanering's Extractive Cleaning of Cyanide Contaminated Sandy Soils--The HWZ [13] plant, with soil handling capacity of 20 ton/hr, has been in operation since 1984. The process scheme consists of separating the coarse material (>10 mm); intensive mixing of soil and NaOH in a scrubber; washing the soil with an extractive agent in an upflow classifier; and separating the coarse sand, low-density particles (coke, grass, etc.), and silt by sieves and hydrocyclone. The extracting agent is cleaned by pH adjustment followed by flocculation and coagulation. The cleaned extractive agent is recycled. Table 5 shows some of the results of the HWZ soil cleaning runs. The extracting agent used in the soil cleaning process was a detergent [13].

Ecotechniek's Thermal Washing Installation for Cleaning Sandy Soil Contaminated with Crude Oil [13]--This installation, in full-scale operation since 1982, has a 20 ton/hr soil handling capacity. The process consists of slurrying sand with water and indirectly heating with steam to a maximum of 90°C. Oil is dispersed in water, and any floating oil is skimmed off. The sand is separated from the water, and the process water containing oil is cleaned by sedimentation and skimming operations. The process is suitable for separating crude oil that is less dense than water. The process temperature is dependent on the type of oil to be separated. So far, 5,000 tons of beach sand contaminated by oil spills have been cleaned using this process. Sands containing 200,000 ppm of oil were cleaned to the 20,000 ppm level. The treated sand was recycled for use in preparation of asphalt.

Bodemsanering Netherlands (BSN) High Pressure Washing of Sandy Soil Contaminated with Oil [13]--This installation, in operation since 1983, separates oil from sandy soil. The plant has a 20 ton/hr soil handling capacity and is transportable. The process consists of separating coarse material (>100 mm) by sieving; high pressure jet washing of soil (<100 mm); separation of coarse sand by sieves and hydrocyclone (>63 um); separation of silt by sedimentation; separation of process water, oil, and fine mineral fractions (<30 um) by oil/water separator and use of coagulants and flocculants. An option is additional microbiological treatment of treated sand and spent process water. The water is recycled to a high-pressure washer. Table 6 shows the results of some of the BSN runs.

TABLE 4. SELECTED RESULTS FROM HEIJMAN'S SOIL CLEANING RUNS*

Contaminant	Initial concentration (mg/kg)	Concentration after treatment (mg/kg)	Removal efficiency (%)
Mineral oil	3,000-8,000	90-120	approx. 98
Galvanic CN	450	15	approx. 94
Zn	1,600-3,200	300-500	approx. 83
Cd	66-125	5-10	approx. 92
Ni	250-890	85-95	66-89

*Source: Reference 13.

TABLE 5. SELECTED RESULTS FROM HWZ SOIL CLEANING RUNS*

Contaminant	Initial concentration (mg/kg)	Concentration after treatment (mg/kg)	Removal efficiency (%)
CN (gaswork)	100-200	approx. 10	approx. 95
PNA (gaswork)	36	0.7	98
Chlorinated hydrocarbons	20-24	0.3-0.5	98
Zn	81	27	67
Pb	approx. 100	approx. 25	approx. 75

*Source: Reference 13.

TABLE 6. SELECTED RESULTS FROM BSN SOIL CLEANING RUNS*

Contaminant	Initial concentration (mg/kg)	Concentration after treatment (mg/kg)	Removal efficiency (%)
Aromatics	240	45+	81+
PNAs	295	15	95
Crude oil	79,000	2,300	97

*Source: Reference 13.

+The concentration of aromatics was reduced to 10 mg/kg on account of microbiological activity 6 months after treatment.

Klockner Umweltechnik, using a version of the BSN process, blasts soil particles with a high-pressure water jet (5075 psi) to clean contaminated sandy soils [14]. Klockner uses a circular water jet nozzle arrangement. Test run results are shown in Table 7.

The process has potential for cleaning all types of soils with fines (<63 um) not exceeding 20 percent. The developer claims the soil can be cleaned of the following contaminants:

- all aliphatics and aromatics with low densities (less than water);
- volatile contaminants; and
- some water soluble and biodegradable hydrocarbons.

Harbauer Soil Cleaning System [15]--This wet extraction process uses hydraulically produced oscillation or vibration to achieve the initial separation of soil particles and contaminants. The prepared soil is mixed with water and chemicals and is introduced into a decontamination chamber where a vibrating screw conveyor moves the soil forward under constant vibration. Hydraulically produced oscillations or vibrations at high energy are applied axially to the conveyor to vibrate the soil particles and separate the contaminants. The soil cleaned is separated from the extraction by stages. In the first stage, coarse soil fractions (15 mm to 130 um) are separated by sedimentation. In the second stage, medium soil fractions (130-20 um) are separated by 5-step hydrocyclone. In the third stage, fine soil fractions (20-15 um) are separated by vacuum filter press. The water is cleaned using counter-current flotation and flocculation, followed by air stripping and activated carbon filtration.

The treated water is recycled. Table 8 shows the results of a test run with contaminated soil excavated from the Berlin-Mariendorf gas works location. The soil grain size distribution shows that 37 percent of the soil fractions are less than 100 micron in size. The unit has an average throughput of 40 tons/hour with recovery of 95 percent of input soil by volume.

EWH-Alsen-Breitenburg Pilot Plant to Clean Sandy Soil Contaminated with Oil [16]--This pilot plant (DEKOMAT System) uses special reagents added to water to clean sandy soil. After separation of large particles (>80 mm) by grizzly screens, the reagent, soil and water are mixed in a high-shear stirred tank. The cleaned soil is separated with different fractions using vibrating screens, screw classifiers, hydrocyclones, and sedimentation tanks. The oil is skimmed by an oil skimmer, and fine particles are separated by use of a flocculant. The water is recycled. The clean soil is analyzed for residual contamination and sent for redeposit. The clay and skimmed oil are analyzed for hazardous material and either sent to a special incinerator for burning or if clean used in cement production. The pilot plant has operating capacities of 8 to 10 cubic meters/hour. The water to soil ratio is 1:1, and 95 percent cleaning efficiencies are reported by the developer.

TABLE 7. SELECTED RESULTS FROM KLOCKNER SOIL CLEANING RUNS*

Contaminant	Initial concentration (mg/kg)	Concentration after treatment (mg/kg)	Removal efficiency (%)
Hydrocarbons	2,222	82.05	96.3
Chlorinated hydrocarbons	0.04	<0.01	100
Aromatics	12.4	<0.02	99.8
PAHC	333.0	15.48	95.4
Phenol	5.44	<0.01	100.00+

*Source: Reference 14.

+Phenol is highly soluble. Complete removal is expected and does not indicate that this system is superior to others.

TABLE 8. SELECTED RESULTS FROM HARBAUER SOIL CLEANING RUNS*

Contaminant	Initial concentration (mg/kg)	Concentration after treatment (mg/kg)	Removal efficiency (%)
Petroleum ether extract	476	67	68
PAHs	752	2	99.7
Phenol	60.5	ND	100
Total Cyanide	5.3	0.059	98.9

*Source: Reference 15.

Lee's Farm Lead Extraction from Soils [17]--In 1985, a lead-contaminated soil at an NPL site was screened and crushed to <50 mm. The crushed soil was washed by a 30 percent EDTA solution, using an inclined-screw washing unit. One part of soil was mixed with three parts of extractant in a hopper at the lower end of the screw. The equipment was operated solely as a batch unit because the soil contained too many fines, overwhelming the ability of the equipment to continuously separate the clean soil from the extractant. The test information is being used to specify equipment that can handle clays for future pilot-plant work at this site or other NPL sites.

EPA's Mobile System for Extracting Spilled Hazardous Materials from Excavated Soil [18,19]--Pilot studies were performed to determine the equipment train. Three unit operations were developed and tested:

- Water Knife--A thin, flat, high-speed jet was optimized to break up clumps of soil and scrub contaminants from larger soil particles like stone and gravel. Testing showed that this concept is very effective.

- Rotary Drum Screener--A rotary drum was employed as a pretreatment to mix the soil with the extractant and to separate the coarse and fine particles.

- Extraction and Separation Concept--A four-stage counterflow extraction process was built employing hydrocyclones between each extraction tank to separate the soil and washing fluid. Contaminated soil is fed to the first tank and mixed with extractant from the first hydrocyclone. Froth flotation is used to produce maximum mixing between the soil and extractant. The slurry collected from the bottom of the tank is pumped to the first hydrocyclone. Solids from the hydrocyclone are mixed in the second tank with extractant from the second hydrocyclone. This procedure is repeated until the cleaned soil is removed from the fourth and final hydrocyclone. Spent washing fluid is withdrawn from the first stage, while fresh extractant is added to the fourth stage tank.

Hot Water Process for Extraction of Oil from Tar Sand [20]--The sand is mixed with hot water and violently agitated to mobilize the oil. The sand/oil mixture is continuously separated in a settling tank. The oil froth overflows the tank and is separated by a centrifuge. Water is added to the centrifuge to form another layer between the oil and sand.

Gasoline Removal from Sand [21]--A fixed-bed pilot test program was sponsored by the American Petroleum Institute using a sand bed. Surfactants were used to enhance the recovery of gasoline. The sand bed was about 3 square meters by 1.2 meters deep. Multiple applications by percolation resulted in good recovery of the gasoline.

Post-treatment Experience--

Treatment of the contaminated extractant is required so that purified water and recovered additives can be recycled. Processing of a contaminated extractant is similar to processing polluted water, which is a mature science [22]. Equipment is readily available for the processing unit operations discussed below.

Biological Treatment--Most organic contaminants can be destroyed biologically. Work at Rutgers University is extending this established treatment concept to the field of hazardous waste [23,24]. The key unit operation is a biological treatment bed for destroying organic chemicals in an aqueous extractant.

Coagulation and Sedimentation [25]--Additions of coagulant and flocculant to contaminated water can separate the colloidal organic and inorganic contaminants from the water. This technique is also useful for removing fine soil particles from the extraction fluid.

Ion Exchange--This technique is usually a polishing treatment for low levels of ionic contaminants. In the case of radioactive contaminants, the technique applies as a primary cleaning method.

Activated Carbon--Most organic contaminants are removed from water using the carbon filter. This technique is the most useful in cleaning low levels of toxic organics.

Supercritical Oxidation [26]--This wastewater treatment process is very effective in destroying all organics. Oxygen stored as liquid is fed to a pressurized vessel with the aqueous slurry waste feed. The vessel is heated and pressurized to approximately 400 to 650°C and 220 to 250 atm (above the critical point) to destroy the contaminant. An additional benefit is that some inorganics separate out from the supercritical water. End products are innocuous: N_2; CO_2; salts such as $CaSO_4$, $MgSO_4$, and Fe_2SO_4; and clean water.

Photochemical Destruction [27, 28]--Ultraviolet light enhances chemical reaction rates. This technique allows for destruction of organics at moderate temperature. Oxidizing agents are added to enhance the destruction of organics.

Oxidizing Agent [29]--Oxidizers such as chlorine, hydrogen peroxide, and ozone are used to destroy organics.

Electrolysis [30]--Electrolysis provides the means to regenerate the chelate and recover the metal.

Volatile Stripping of Organics from Water [31,32]--Volatile organics can easily be stripped from water in a scrubbing tower. The contaminant can be either vented to atmosphere or destroyed by incineration.

Filtering--Fine particles in the extractant can be removed by a filter. The use of sand, diatomaceous earth, or some other type of porous disposable layer might be required instead of conventional reusable filter material, because soil fines may permanently plug the filter material.

Other filtration/separation techniques that may be useful in removing fine particles from the extraction water include microfiltration, ultrafiltration, hyperfiltration, and nanofiltration. The use of mechanical cleaning or air or water actuated backwash techniques may mitigate fouling of the filter media.

The postextractant treatments discussed above have not been demonstrated fully for treating soil. Operating experience on a complete above-ground soil cleaning facility is very limited. Existing studies are primarily at the pilot level.

Procedures for Contaminant Removal from Soil

Hydrophilic Organic Contaminants Removal--

A hydrophilic organic is an organic compound that is soluble in water. Examples of hydrophilic compounds are methylene chloride and aldehydes. Important process parameters and experience in removal of hydrophilic compounds from soil matrices are discussed below.

Process Parameters--

- pH--For some organics, manipulation of pH is useful to improve the mobility of the contaminant into solution. For example, phenols are easily mobilized with an alkaline solution. Reversing pH can be used to separate the organic from water in a postextractant treatment step.

- Humic Content in Soil--Humus in soil contains bonded water, colloids, and chelates that retain the contaminant. A caustic solution is used to free these contaminants by altering the surface charge of the humic substrate allowing solubilization of the contaminants.

- Agitation--A turbulent mixing process is required to disperse the soil in the washing solution and to provide abrasion to break down inhibiting film conditions in the soil.

- Time, Soil Loading, and Staging--Extraction time may be a more important variable than water to soil ratio or number of extraction stages. The economics will dictate the design specifications of these variables.

- Wetting Agent--A wetting agent may be required to improve the penetration of the water into the soil particles to mobilize the contaminant.

Specific Experience--Hydrophilic contaminants are effectively removed by in situ pump and treatment techniques. Therefore, the opportunities for above-ground cleaning are limited. The only naturally occurring mechanism competing for hydrophilic compounds in soil is the presence of humus in the soil. Humic material (colloids) present above 1 percent and high contaminant levels may favor above-ground treatment [33].

Hydrophobic Nonvolatile Organic Contaminants Removal--

A hydrophobic organic is defined as being insoluble in water. However, some hydrophobic organics with an octanol/water partition coefficient between 10 and 1,000 are referred to as slightly hydrophilic. These organics tend to be found in the ground water because of natural washing by ground water movements. The slightly hydrophilic organics are more easily washed than the insoluble organics. Typical slightly hydrophilic compounds are aromatics and halogenated hydrocarbons. Insoluble hydrophobics commonly found at NPL sites are pesticides, heavy oils, and greases.

Process Parameters--

- Surfactants--Surface active agents are added to the water to reduce the surface tension between two liquids or a liquid and a solid. Surfactants provide the link between water (a polar compound) and the hydrophobic contaminant (a nonpolar compound). Aqueous surfactant washing is not applicable to soils with a high humic content.

- Caustic Agent--Soils high in humic content require a high pH solution (pH 12) to mobilize some contaminant from the humus. The caustic breaks down the organic structure and mobilizes the contaminant if the contaminant does not react with the caustic to form an insoluble compound.

- Extraction Stages--More than one extraction step is required. The contaminant level should be reduced by one order of magnitude per step. The residence time in each step should be long enough to achieve this reduction. The hydrophobic contaminant level at NPL sites varies between 100 and 10,000 ppm, and thus may require two to four stages of extraction.

- Agitation--Mixing is required to disperse the soil, but excessive mixing will produce large amounts of sludge. The mixing should aid in mobilizing the organic, but not be so intensive as to create an excessive amount of fines which adds to the problem of soils washing.

- Temperature--A temperature near the boiling point of water (can be a slightly pressurized system) should aid in mobilizing the contaminant. The contaminant is removed as a froth from each stage.

- Reactor Configuration--For contaminants that are slightly hydrophilic and permeable, a fixed-bed arrangement is satisfactory. For insoluble hydrophobics, a constantly stirred reactor is required.

- Solid-to-Extraction Solution Ratio--A ratio of one part solids to one part extraction fluid is preferred to minimize the treatment of the extractant. However, two to three parts of extraction fluid is a more practical range with respect to equipment operation.

Specific Experience--The most recent and thorough investigation of aqueous surfactants used for soil cleaning is discussed in a report sponsored by the EPA [33]. Sandy soil with low humic content (<1/2 percent) was spiked with two hydrophobic compounds-- crude oil and transformer oil containing PCBs. Crude oil (1,000 ppm level) was reduced by 93 percent using 2 percent each of Adsee 799 (Witco Chemical) and Hyonic NP-90 (Diamond Shamrock) surfactants. The extent of removal of PCBs was 92 percent for 0.75 percent of each surfactant.

Similar soil cleaning studies using surfactants were conducted by the Texas Research Institute [21]. Gasoline was recovered from sand in a pilot study by percolating an aqueous surfactant solution through a bed of gasoline-contaminated sand using a combination of commercially nonionic (Hyonic, PE-90) and anionic (Richonate, YLA) surfactants. Multiple washing recovered 76 percent of the gasoline.

A bench-scale study conducted by Rutgers University in cleaning sandy loam soil contaminated with organics showed 92 to 95 percent removal efficiencies using a combination of 2 percent each of Adsee 799 and NP 100 surfactant (private communication, Dr. Rajput, Rutgers University, April 1988.)

Heavy Metals Extraction Using Chelating Agents--

All metal cations have one or more "reactive" sites available to ligands (molecules that can bind to a metal ion to form a complex). An interaction occurs at reactive sites between positively charged metal cations and electron-donating ligands to form complexes. Chelants are ligands that form multiple chemical bonds in a ring structure [34]. Chelants react with metals in ionic form only, not in a free metallic state.

Chelation may be defined as achieving an equilibrium between a metal ion and a complexing agent, characterized by the formation of more than one bond between the metal and a molecule of the complexing agent and resulting in a ring structure incorporating the metal ion.

Process Parameters--

- Effect of Other Metal Cations--A stability constant measures the affinity of a metal for a particular chelant. The greater the affinity, the greater its ability to displace other chelated metals. This preferential chelation occurs at a thousandfold stability difference between metals [35]. Naturally occurring soil-bearing metal cations compete for the chelating agent with the contaminant metal ions requiring excessive chelate quantities. However, proper pH control and chelate selection may minimize this effect.

- Effect of Other Anions--Anions have little effect on chelation. However, sulfide anions form very stable metal sulfide complexes, which may be useful in regenerating spent chelation solutions.

- Soil Classification--Process problems resulting from the silt/clay soil fraction have been encountered in previous efforts to extract lead from soil [36]. Solid/liquid separation difficulties and failure to decontaminate the silt/clay fraction can be eliminated by classifying soil into its constituent fractions before or during chelation. Remediation methodology and equipment can be adapted to each classified fraction.

- Temperature--Temperature has a negligible effect on chelation. Chelant-metal complex stability decreases one order of magnitude per 55°C increase [35].

- Ionic Strength Effect--An ionic equilibrium exists within the chelant-metal complex. Although a large concentration of ions not participating in chelation lowers the complex stability, the effect is negligible [35].

- Chelant Concentration--The amount of chelant needed to react with a unit weight of a specific metal is provided in manufacturers' literature; this quantity should be verified by laboratory tests [35]. For continuous processing of soils, additional considerations in determining chelant quantity are chelant solution viscosity and the amount of chelant needed to drive the reaction to completion.

- Chelation Duration--If the objective is to chelate the maximum amount of metal, then empirical determination is necessary to obtain the reaction duration (retention time).

- Soil Loading--The chelating solution-to-soil ratio must be high enough to allow proper mixing. However, as the ratio increases, reactor size, number of reactor vessels, or both increase. If the chelant-soil mixture reaches chemical equilibrium, soil loading must be balanced with spent chelant removal and fresh chelant introduction rates.

- pH--pH is one of the most important parameters of the system. Both metal cation and chelating agents are influenced by hydrogen ions. Hence any change in pH affects the equilibrium of the system [35]. Since stability constants are pH dependent, an adjustment of solution pH may favor the formation of a preferred metal complex. For example, pH 7 to 9 favors lead (II) chelation over the generally more stable Fe(III), so contaminated soil may be treated without significantly extracting the ubiquitous iron.

Specific Experience--Metal chelation research has examined metals to soil binding and metal availability for removal of metal from the soil. Soil treatment research has focused on in situ metals chelation with low concentration, mild extractants. Limited extraction work on excavated soil has yielded encouraging metal reduction results, but has encountered soils handling problems. DTPA sludge extractions by Silviera and Sommers yielded maximum removals of 50, 29, 40, and 30 percent for total Pb, Zn, Cd, and Ca, respectively [37]. Brown, et al., reported the percentage of extractable metals for removal in sludge-treated Padina soil was as high as 105, 84, 56, 178, and 46 percent for Pb, Zn, Ni, Cd, and Ca, respectively [38].

In EDTA chelation experiments for in situ treatment Connick, et al. preadsorbed metal salts onto Typic Hapludults (fine to coarse loamy) soil contained in columns and rinsed with 0.144M EDTA, achieving 63, 93, 94, 100, and 82 percent removal of Pb, Zn, Ni, Cd, and Cu, respectively [39,40]. During soil leaching studies, extraction of preadsorbed clays by Farrah and Pickering showed EDTA effectiveness on the strongly binding clay fraction [41]. Some researchers assert that metal-soil binding changes with time until an equilibrium is established [38,40]; hence preadsorbed soils used in the previous extraction studies may not be representative of "mature" NPL soils. Ellis and Fogg used an EDTA/hydroxylamine/citric acid sequential extraction for in situ remediation of Western Processing, Inc., NPL site soil, reducing Pb, Ni, Cd, Cu and Cr by 96, 22, 100, 75, and 52 percent, respectively [34]. Their multiagent extraction was more effective than a single-step EDTA chelation, because a greater range of metal binding mechanisms was vulnerable to release.

Other chelants reduced lead content in soil at Church of God in Leeds, Alabama, by 95 percent with ammonium pyrolidinecarbodithioate (APOC) [36]; and EPA reported that "NTA did not work as effectively as EDTA" in chelating lead from the soil at the Lee Farm in Woodville, Wisconsin during laboratory studies [42,43].

Recent pilot-scale chelation studies on excavated soils have produced promising results. The USEPA Releases Control Branch, utilizing 13 to 16 percent EDTA chelant, removed 94 to 97 percent of total lead from Church of God soil using the 4 to 5 ton/hr capacity screw extractor. At the Lee Farm, USEPA Region V reduced gross lead contamination below the EP toxicity limit of 5 ppm leachable lead in laboratory-scale EDTA chelations. However, during production-scale treatment, the broken battery casing fraction alone was decontaminated below EP Toxicity requirements [42,43].

Soil-handling problems at both sites included:

- Clogging of plate and frame filter presses due to silt and clay;
- Plugged pumps, worn augers, and difficulty in handling sands;
- Large quantities of chelation solution carryover into rinse tanks; and
- Solid/liquid separation of silt and clay between process steps.

To eliminate some of the problems encountered at the Lee Farm, Enviresponse, Inc. (EI) under USEPA Emergency Response Team (ERT) auspices classified Lee Farm soil into three fractions (0.25 in.; 100 um-0.25 in.; <100 um) before laboratory EDTA chelation. They achieved 700 ppm residual total lead in the 100 um-0.25 in fraction, a 95 percent reduction, while maintaining EP toxicity values within limits [17]. By adjusting the EDTA solution to pH 7, thereby maintaining a high stability constant for lead over iron, these researchers chelated little Fe(III) in the high-iron-bearing soil.

Heavy Metals Extraction Using Acids--

Heavy metals can be extracted from soil by using acid as an extraction agent. This is a common technique for extracting minerals from ores. The heavy metals are separated from the acid solution either by precipitation or ion exchange.

Process Parameters--

- Extractant Type--Factors to consider in choosing an acid are effectiveness, safety, disposal, and cost.

- Extractant Concentration--Acid extractant concentrations have varied greatly (e.g., 0.001M HNO_3 to concentrated HNO_3) [41,44]. If the release of metals occluded in coprecipitates as oxides and sulfates is desired, then higher acid concentrations are necessary. The literature reported that extractant concentrations vary greatly; therefore, experimental data are needed to determine the appropriate concentration to obtain a desired reaction product.

- Soil Loading--As with soil chelation, the extractant-to-soil ratio should allow for intimate mixing. The soil loading should be low enough to allow maximum metal extraction at a particular extractant concentration.

Specific Experience--Singh and Narwal [44] state the following order of extraction performance for removing metals from sewage sludge-treated soil: HNO_3 > Aqua Regia > HCl > NH_4OAc (pH 4.8). However, different concentrations used in this study make acid comparisons difficult. A treatment study at the Celtor Chemical Works site in Hoopa, California utilizing sodium glutonate solution, EDTA, acetic acid, hydrochloric acid, or hydrochloric acid/hydrogen peroxide, found that "none of the extractants were capable of producing a soil below cleanup level for all metals" [45]. This study reported that lead removals were poor for hydrochloric acid and acetic acid extractants, although lead removals were up to 44 times greater for hot HCl vs. ambient HCl. The removal pattern for HCl-H_2O_2 was similar to the pattern for HCl. On the other hand, an ammonium carbonate-fluorosilicic acid extraction of the Lee Farm classified soil (100 um to 0.64 cm fraction) was performed by Cole at the U.S. Bureau of Mines in Rolla, Missouri. This process reduced total soil lead in this fraction to 500 to 800 ppm--a 94 percent reduction from an average initial lead concentration of 10,749 ppm [17].

The Muller leaching process extracts heavy metals from contaminated dredged materials, sludges, combustion residues and soils. After the heavy metals are extracted with HCl, the solids are separated from the filtrate. The heavy metals are removed using hydroxide and carbonate precipitation. The remaining filtrate contains <1ppm of heavy metals. The intital concentration was not reported [46].

SOLVENT EXTRACTION

General Process Considerations

Solvent extraction using organic solvents could be used to clean soil contaminated with high concentrations of nonvolatile hydrophobic organics. Hydrophilic organics are most effectively removed by water washing, as discussed previously. The choice of suitable solvent depends primarily on chemical structures of the contaminant, solvent extractive capacity, soil type, and equilibrium characteristics. In addition to these, the solvent should be stable and must have favorable density, viscosity, and interfacial tension properties. There should be a sufficient difference between the boiling points of the solute and the solvent to facilitate post-treatment separation.

In general, the ideal solvent for the task should not be volatile at low temperatures; should be pure, noncorrosive, nonviscous, nonfoaming, nontoxic, and nonflammable; should have infinite solubility for the solute(s); and should be inexpensive. Zoltek and Earle [47] list possible solvents for different contaminants. The rule "like dissolves like" provides good guidance [48]. For example, nonpolar heavy oils are extracted by a nonpolar solvent such as hexane.

Process Unit Description

Solvent extraction of the organic contaminant takes place in either one or a series of pieces of equipment called extractors. The equipment, as well as the general arrangement of the plant, is highly dependent on the nature of the contaminant and its relative solubility in the chosen solvent. Leaching and immersion extraction are the two general extraction techniques.

Leaching Extraction--

In its most typical form, leaching is a batch extraction operation in which the screened soil is deposited in a false-screened bottom tank(s) inside retaining walls, and solvent is sprayed over it. The solvent leaches the contaminant from the soil. The contaminant-rich solvent is collected at the bottom after it has percolated through the soil. In the absence of agitation, the liquid-solid extraction is slow and not very efficient. Liquid channeling through the soil can lower further the extraction efficiency, leaving a portion of the soil unextracted. The presence of fines can stop the percolation process. On the other hand, coarse agglomerates with a well-imbedded contaminant often can be cleaned at the surface only. At the end of the extraction process, the soil retaining the solvent is dropped through the false bottom, and another batch is started.

For a single batch extractor, contaminant-free solvent is sprayed until the bottom solvent shows no traces of contaminant and the extraction can be considered total. The process is slow and requires large amounts of solvent; the rate of extraction decreases with contaminant concentration.

To overcome these disadvantages, a battery of extractors can be operated in countercurrent extraction. The more fully extracted soil is leached with virgin solvent; the raw contaminated soil is the last in the extraction line.

Immersion Extraction--

For low-solubility contaminants, fine soils like clay and silt, or soils with a very low residual contaminant content, the leaching process is unacceptable due to slow mass transfer rates. For these cases the solid is dispersed into the liquid in an immersion extraction.

In its simplest form, an immersion extractor is an agitated tank filled with the solvent, in which the soil is suspended and thoroughly mixed. When the extraction equilibrium has been reached, the agitation is stopped and the solid is allowed to settle. The solvent is drained and fresh solvent can be used for a second step extraction. The countercurrent extraction concept described for leaching extraction also applies for immersion extraction.

Soil-Solvent Separation--

Soil-solvent separation can be a simple unit operation or a cumbersome series of unit operations. For coarse, easy-draining soils such as gravel and sand, the solvent is just drained from the soil. For hard-to-settle fines, such as clay or silt, the operation will require mechanical solid-liquid centrifuges.

Residual Solvent Removal--

Granular solids retain liquids because of surface adherence forces and interstitial surface tension forces. The higher the viscosity and surface tension of the liquid and the smaller the granules of the solid, the more solvent is retained in the solid bed. Selected solvents are expected to have low viscosity and surface tension, which will reduce liquid retention. Fine soils, high surface adsorption materials, or colloidal suspensions tend to retain large amounts of solvent.

The most easily treated soil is a coarse sand which will retain, after free gravity drainage, approximately 2 to 3 weight percent solvent. For finer grained soils, centrifugation or thermal desorption may be necessary to obtain low solvent residuals.

Solvent Displacement--

Most, if not all, of the organic solvents are undesirable contaminants in soil and, regardless of the cost of the lost residual solvent, must be eliminated from the soil before reburial. Some examples of elimination processes are solvent displacement, gas or vapor stripping, and steam stripping.

Solvent displacement is another solid-liquid extraction process where the new solvent is nontoxic and is left in the soil. The initial extraction solvent must be totally miscible with the displacement solvent. The least expensive and most nontoxic displacement solvent is water. Unfortunately, most good organic solvents (e.g., hydrocarbons or halogenated hydrocarbons) are not soluble in water, and this method cannot be applied. Alcohols, ketones, and esters are classes of solvents with high miscibility with water; consequently, displacement of the residual solvent with water is possible. Process considerations and equipment used for solvent extraction also apply for this displacement process. Gas, vapor stripping and steam stripping are processes similar to volatile organic contaminants stripping, described in detail later.

Solvent Recovery--

Environmental and economic considerations require solvent recovery and reuse of the recovered solvent. As initially discussed, to obtain a high level of solvent recovery, a recommended solvent must have a relatively low boiling point quite different from the contaminant boiling point. The most used and recommended solvent recovery method is distillation. The recommended solvent need not be totally contaminant free. Small amounts of contaminant may be recycled in the soil extraction.

Another possible, though unlikely, solution for solvent recovery is a chemical reaction of the contaminant with the formation of a precipitate, an immiscible phase, or a nontoxic component. In these cases a precipitate can be separated by filtration and a nonmiscible phase by liquid-liquid separation; the nontoxic compound can be left to accumulate in the recycled solvent until its concentration interferes with the extraction process.

Related Experience

Pertinent experience in commercial solid-liquid extraction applied to large amounts of solids includes ore, tar sand, and sugar beet extraction. In all these processes, the extractor contributes substantially to the capital and operating cost of the whole plant. Consequently, a substantial engineering effort has been put into developing continuous extractors. Theoretically, continuous extraction can be operated in co-current, cross-current, or counter-current modes. Consideration of the thoroughness of extraction and solvent consumption make the counter-current extraction the only commercially feasible option.

Starting from the battery of extractors concept, Dravo Corporation developed the Rotocel Extractor. In this extractor (Figure 2), the material to be extracted is fed continuously as a slurry with the extraction solvent or as a dry feed to sector-shaped cells arranged around a horizontal rotor. The cells have a perforated base to permit the solvent to drain into stage basins, from which, on the countercurrent principle, it is pumped to the next cell. In the last cell, where fresh solvent is supplied, an extended drainage period is provided (by allowing a proportionately larger arc of the rotary motion for this cell); thereafter, the extracted solids are dumped. In addition to being

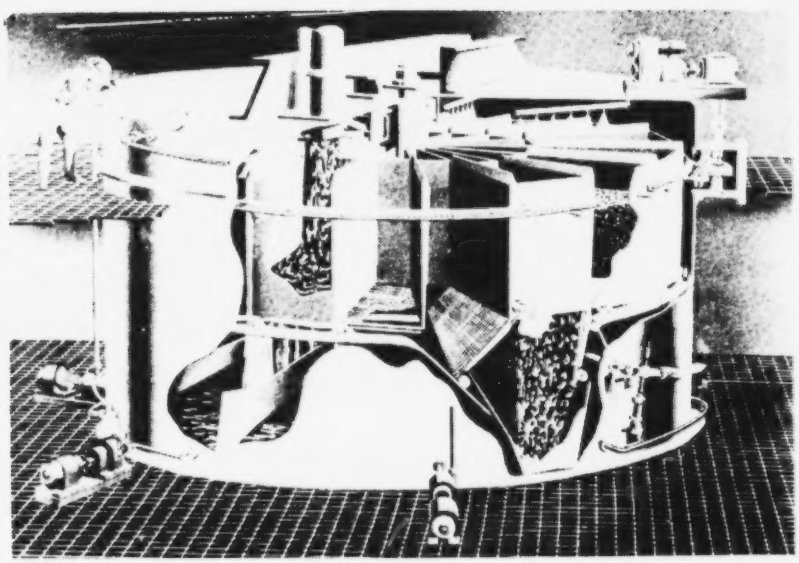

Figure 2. Rotocel percolation extractor. Courtesy of Dravo Corporation. Reprinted from Encyclopedia of Chemical Technology, 3rd ed. Vol. 9 by Kirk-Othmer; Copyright © 1979. Reprinted by permission of John Wiley and Sons, Inc.

filtered by the bed of material being extracted, the fines are filtered over a tent screen before complete solvent removal. Rotary extractors similar in principle to the Rotocel are offered by other equipment manufacturers. Filtration of the fines over a bed of coarse material has been claimed to achieve solvents with less than 5 ppm suspended solids [48].

Another continuous extractor is the Endless-Belt Extractor; its principle operation is similar to the Rotocel. Two key parameters, extraction time and percolation rate, determine belt speed and the required drainage area, respectively. Since bed height is virtually fixed by the mechanical design of the extractor, these parameters control the plant capacity. A low percolation rate could make the required drainage area prohibitively large. Solvent, which can be fed by spraying or simply from overflow weirs, may be used in a simple counter-current manner or, where the percolation rate is high, may be recycled internally to improve the approach to equilibrium [48].

The Lurgi Frame-Belt Extractor (Figure 3) has a two-tier system in which the solid material travels the length of the extractor while being extracted in an upper series of compartments (frame buckets), with the perforated endless belt serving as a false bottom. The bed is then partially drained of solvent and discharged into a lower series of compartments. There extraction continues with an increasingly leaner solvent until reaching a final drainage zone before discharge of the exhausted solids [48].

The De Smet Belt Extractor (Figure 4) uses a single endless belt to hold the material being extracted. The risk of solvent migration is minimized by rakes that penetrate the upper 150 mm of the bed (overall bed height 1.3 to 1.8 meters) to form ridges of solid material at intervals. The rakes also break up the upper layer of the bed to maintain steady percolation conditions. The belt moves discontinuously, providing a clearly defined extraction period followed by a drainage period [48].

The immersion extractors have the ability to handle fines and to extract materials with low diffusion rates. This type of process is used for the extraction of sugar beets, oil seeds, or trace pigments and pharmaceuticals from plant materials. Continuous immersion extractors were originally constructed in tower forms, and such designs have maintained an important place in the sugar industry.

The BMA Diffusion Tower has a central shaft fitted with a series of inclined plates that direct movement of the solid material. The tower shell is also fitted with a series of staggered guide plates that serve the same purpose. Another tower extractor, in this case designed and built by Wolf, also employs the principle of wings attached to the central shaft to transport the solid material to be extracted up the tower. In both cases sugar beets are fed to the base of the tower. The towers are commonly 10 to 15 meters high; different capacities are achieved by variations in tower diameter. In either form of construction, power consumption for a 5.5 meter diameter tower (capacity: 3,000 metric tons of beets per day) is about 40 kW [48].

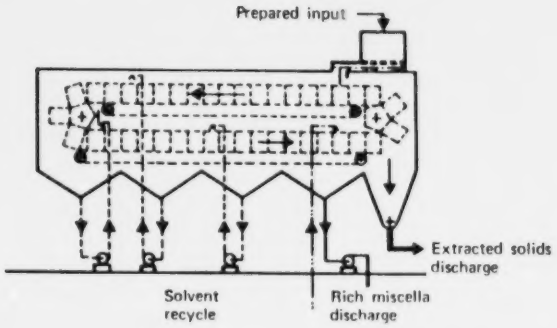

Figure 3. Lurgi frame belt extractor. Courtesy of Lurgi Umwelt und Chemotechnik G.m.b.H. Reprinted from Encyclopedia of Chemical Technology, 3rd ed. Vol. 9 by Kirk-Othmer; Copyright © 1979. Reprinted by permission of John Wiley and Sons, Inc.

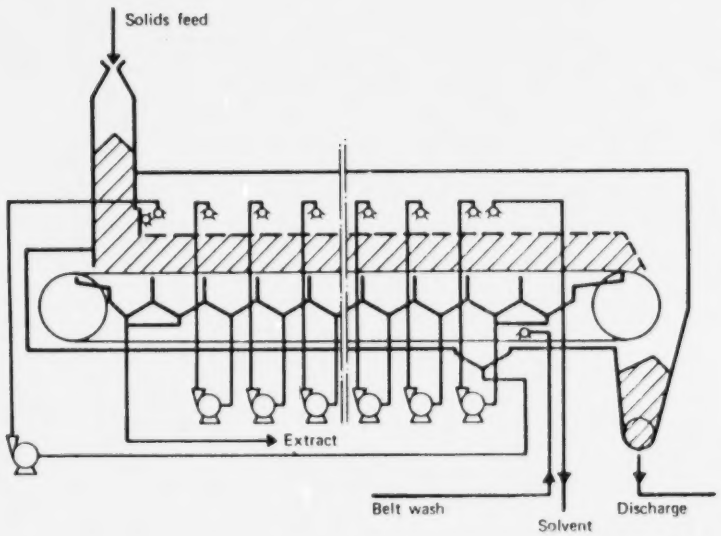

Figure 4. DeSmet continuous-belt extractor. Courtesy of Extraction DeSmet, S.A. Reprinted from Encyclopedia of Chemical Technology, 3rd ed. Vol. 9 by Kirk-Othmer; Copyright © 1979. Reprinted by permission of John Wiley and Sons, Inc.

The De Danske Sukkerfabriker (DDS) diffuser extractor (Figure 5) may be regarded as a tower extractor with its axis turned about 80°. The extractor is normally installed at a one (vertical) to seven (horizontal) slope, and a double screw in the housing is used to transport the solids. The operating temperature is reached by employing jacket heating, thus avoiding the requirement for preheating. The dimensions of the DDS diffuser and its power consumption are, broadly speaking, similar to those of the tower extractors [48].

The use of these immersion extractors is contingent upon the ability to transport solids without excessive back mixing. They need less space than percolation extractors and lower power for the band drive and liquor circulation [48].

The need to improve the desired product removal yield and to reduce the contact time led researchers to introduce extra energy into the extraction process. The most successful attempt seems to be the use of ultrasonic energy along with immersion extraction. Using acetone as a primary extraction solvent with heptachlor epoxide, contaminants were extracted in the laboratory with ultrasonic waves; results were better than with the simple solvent extraction [49]. Ultrasonic energy plus slow stirring enhancement was used for removing the bitumen from tar sands with good results. Solvent extraction pilot study results showed that ultrasonic energy plus slow stirring achieved 78 percent bitumen removal after 30 seconds, while stirring alone achieved only 63 percent removal after 4 hours [50].

Procedures for Contaminant Removal from Soil

Nonvolatile Organic Contaminants--

Nonvolatile organic contaminants can be hydrophilic or hydrophobic organics. Both types of these organics can be handled by solvent extraction. Commonly found hydrophobic organic compounds at NPL sites are pesticides, heavy oils, and grease. Commonly found hydrophilic organic compounds at NPL sites are phenols, methylene chloride, and aldehydes.

Process Parameters--

- Physical Properties of Solvents--Low surface tension increases wetting of the soil and provides for better contact, whereas low viscosity improves diffusion of contaminant into the solvent. Low solvent density reduces the mass of solvent held up in the soil being extracted. The vapor pressure of the solvent should be sufficiently low so that the storage and extraction operations can be carried out at atmospheric or low pressure. The solvent should be nontoxic and nonhazardous.

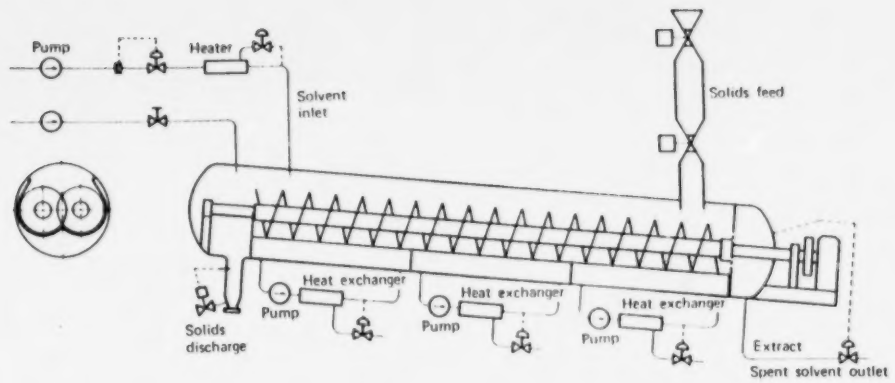

Figure 5. DeDanske Sukkerfabriker (DDS) diffuser. Courtesy of A/S Niro Atomizer. Reprinted from Encyclopedia of Chemical Technology, 3rd ed. Vol. 9 by Kirk-Othmer; Copyright © 1979. Reprinted by permission of John Wiley and Sons, Inc.

- Extraction Stages--More than one stage is required. The residence time in each stage should be long enough to achieve system equilibrium.

- Selectivity--For aqueous extraction varying the pH gives some control over selectivity. With organic solvents, greater selectivity can be obtained by choosing a single solvent or by using a mixture of solvents.

- Solid-to-Extraction Solution Ratio--A ratio of one part solid to one part extraction solution is preferred to minimize the treatment of extractant. However, a ratio of two-to-five is a more practical range.

- Temperature--The choice of the solvent determines the processing temperature that is optimal for mobilizing the contaminants. Certain solvents operate best at low temperatures, others at higher temperatures. Furfural as a solvent is used at relatively high temperature, usually in the 150° to 250°F range. Nitrobenzene is a solvent used at relatively low temperature (in the vicinity of 50°F). Both of these solvents are extensively used in the petroleum refining process.

Specific Experience--Removal of organic contaminants from soil has been limited to laboratory techniques directed toward soil analysis rather than directed toward soil decontamination. Specific laboratory apparatus, such as SOXHLET and POLYTRON, is used; the extraction time is extended beyond any commercially acceptable period (e.g., 120 to 240 minutes) [3].

Experiments with two nonmiscible solvents, water (polar) and kerosene (nonpolar), have been successful in transferring the contaminant to the nonpolar solvent, but end up with high solvent content in the cleansed soil (e.g., 20 to 25 percent) [51,52]. All these experiments were conducted with high solvent-to-soil ratios.

M.B. Saunders [53] describes pilot-scale studies of the Soilex process for removing PCBs from soil. A mixture of kerosene and water was the solvent of choice. A ratio of water-to-soil of 3 together with a kerosene-to-soil ratio of 3 resulted in a slurry having good hydraulic mixing characteristics and yielded a PCB leaching percentage of 84 percent.

The pilot plant consisted of three mixing stages, operated in a counter-current mode. Soil and water were added to stage 1 and clean kerosene to stage 3. Each mix tank had a 200 liter capacity and was mixed with an air-driven agitator. Sampling during the tests showed that equilibrium extraction was achieved in 90 minutes. Kerosene was recovered from the kerosene-water solvent by batch distillation. Kerosene losses in the soil were estimated to be about 25 percent of the kerosene charged. Solid-liquid separation in the pilot plant was by settling and decantation. Kerosene losses were estimated to represent only 2 to 5 percent of the total operating cost. The author reports that the capital cost for solvent extraction was about 50 percent of that for incineration.

The CF Systems Corporation of Cambridge, Massachusetts is currently marketing a system that employs propane as the extractant [54]. Propane at or near its "critical point" is used to contact a 50 percent by weight sludge-water slurry in a reactor. Organic contaminants in the sludge dissolve in the "critical fluid" phase and thus are extracted. Typically, 99 percent of the organics in the sludge are extracted. The "critical fluid" containing dissolved organics is then decompressed. The solvent flashes into a vapor. The organics remain as a liquid. The solvent is recompressed and cooled and recycled to the extraction step as a "critical fluid."

The system vendor indicates that three units will go on stream in 1988. Two units will be fixed installations, and the third will be a skid-mounted mobile unit that can be moved from site-to-site. The mobile unit will have a capacity of 1,000 barrels/day of a sludge-water slurry.

The Basic Extraction Sludge Treatment (B.E.S.T.) [55] process uses triethylamine (TEA), a flammable solvent soluble in water below 65°F and insoluble above 65°F, to extract oil from oily sludges. The sludge and solvent are mixed in an extractor at temperatures below 65°F. The water with dissolved solvent and oil is separated from the solid by centrifuge. The water is heated, and solvent with the oil is separated from the water. The solvent is then sent to a stripping column where solvent is recovered and oil discharged. Hazardous oils and heavy chemicals are recovered and not destroyed by this process. These must be disposed. The B.E.S.T. process is a complex process requiring high degrees of sophistication for operation.

AIR STRIPPING

General Process Considerations

Air stripping is normally used to remove VOCs from soil. To strip volatile organic compounds (VOCs) from soil, the VOC must be vaporized. The stripping may be done at essentially ambient temperatures, or heat may be used to increase the rate of vaporization. Air or steam is the most likely stripping gas. VOCs are removed from a circulating air stream by use of adsorption or combustion. When steam is used as the stripping medium it can be removed by condensation leaving a relatively concentrated vapor of VOC for disposal.

Process Unit Description

In general, any system that is employed in drying solids is applicable to stripping VOCs from soil. These systems consist of:

- A gas/vapor solids stripping device;
- A stripping gas circulating device; and
- A means to remove, recover, or destroy the VOCs in the stripping gas.

When treating soils that adhere and form large particles (i.e., are fine-grained and tend to agglomerate), the following items of equipment may be used for stripping/drying:

- Holo-flite screw
- Rotary kiln/dryer
- Hereschoff furnace

When processing granular free-flowing sandy soils, which disperse easily, fluid bed combustors of the circulating or bubbling type are applicable.

Related Experience

Holo-Flite TM Screw--

The Holo-Flite Screw is identified by name only because it has been specifically tested on soils; however, any similar device would perform as well. Testing performed for the U.S. Army Toxic and Hazardous Materials Agency (USATHAMA) of the removal of VOCs from soil using a Holo-Flite Screw with induced airflow through the trough showed a removal efficiency of 99 percent [56].

The system consisted of a jacketed trough which housed a double-screw mechanism (Holo-Flite.) The screws were 7 inches in diameter and ran the entire length of the trough. The screw shafts and flights were hollow to accommodate circulation of the heat transfer liquid (i.e., hot oil.) The hot oil flowed through the flights in a direction concurrent to the movement of the soil. The oil entered the unit at the soil feed end of the system processor, circulated through the flights, and flowed back through the shaft to exit the unit at the same end that it entered. The trough jacket also circulated hot oil, providing additional heat exchange.

The screws were driven at various rotational speeds via a chain drive connected to the gear reducer located beneath the conveyor. The continuous action of the screws promoted forward movement of the soil through the trough. The screws were set in the trough so that the flights of the two screws intermeshed to break up the soil and improve heat transfer.

Reported process operating conditions are:

- Soil Discharge Temperature 50°C to 150°C
- Soil Residence Time 30 to 90 minutes
- Air Inlet Temperature Ambient (20°C) to 90°C
- Circulating Oil Temperature 100°C to 300°C

Based on the reported test results, this technology appears to provide significant contaminant removal and merits additional investigation on specific contaminated soils. The system has the following advantages:

- Mobile units are available.
- The units can be designed for energy efficiency because of the good contact between the soil and the flights and the relatively low gas flowrate.
- The low gas flowrate reduces the cost of gas treatment facilities.
- Reported soil discharge temperatures are moderate (50°C to 150°C), which should further reduce processing costs.
- The unit should be capable of processing all types of soil. Soils high in clay could be a problem, requiring the addition of gravel that would be removed by screening after treatment and recycled.

A disadvantage of the system is the size of the equipment and the long holding times limiting throughput. This possibly could limit the size of a site applicable to the technology and increase unit processing cost, particularly labor costs.

Rotary Kiln/Dryer--

A rotary kiln is normally used in waste processing as an incinerator. However, if the purpose is to remove VOCs without destroying the character of the soil or to operate at lower temperatures to avoid fouling the walls of the kiln, the temperature in the kiln can be controlled at between 100°C and 400°C.

Rulkens, et al. [11] describe a facility in the Netherlands for cleaning 5,000 tons of soil contaminated with hydrocarbons using a two-stage rotating drum evaporator. Ecotechniek has developed a full-scale system for heating the soil to 200°C to 300°C and releasing the burned vapors in an afterburner at 800°C.

The rotary kiln thermal treatment to remove contaminants from soil by evaporation uses direct or indirect heat transfer to the soil. Direct heat transfer requires large volumes of gas (1 to 2 cubic meters/kg soil) to provide the energy for raising the temperature of the soil. Indirect heating requires one-third less hot combustion gas. The system has the following advantages:

- Can be designed to be mobile;
- Can process any type of soil, but special processing is required for soil with a high proportion of clay; and
- With indirect heat transfer, the airflow can be relatively low.

The following are the disadvantages of the system:

- With direct heat transfer, the gas flow will be high, requiring expensive gas treatment facilities;
- With indirect heat transfer, a very large heat-transfer surface (rotary kiln drum) is required;
- Unless extensive heat conservation is provided, the process will expend large amounts of heat energy;
- Rotary kilns are difficult to seal and since the contaminants are not destroyed in the kiln, it must be operated at negative pressure; and
- Soil containing a high concentration of fines may not be suitable for processing, because prevention of fines entrainment is impossible.

The Hereschoff Furnace--

The Hereschoff furnace is a proven technology used in drying clays and regenerating activated carbon and other solids. To prevent binding and possible breakage of the flights, feed pretreatment to reduce the particle size is required. The pretreated soil, containing water and contaminants, is fed in at low temperature to the center of the top tray, gradually moved by the rotating flights to the outer edge, and falls to the second tray. These rotating flights gradually move the soil to the center, where it falls to the third tray. Access ports are provided on each tray.

The process is repeated with the soil moving back and forth on the trays, falling off the bottom tray of the furnace, and being transferred to disposal. Fired heaters produce hot gases that are introduced into the furnace under the trays. For flexibility, many entrance ports are provided. The point for introducing the hot gases is optional, as is the number of trays. Trays below the point where the hot flue gas is introduced can be used for cooling the soil by introducing air at ambient temperature. The gas moves countercurrent to the soil, and the flights cause the soil to roll as it is moved, thus exposing new surfaces to the gas.

Special precautions are needed when using this technology for treatment of soil containing hazardous VOCs. The unit must be airtight or operate under a slight vacuum. The gas is moved through the unit by an induced-draft fan. The type of gas treatment facilities to be provided depends on the contaminants removed and gas treatment may not be needed in some cases.

The system has the following advantages:

- Temperatures to 500°C are attainable.

- With a sufficient number of trays and proper operation, a reasonable energy efficiency is attainable.

- It is a demonstrated technology. However, whether it has been used to strip VOCs from soils is not known. It is used to burn hydrocarbons from clay.

- With reasonable pretreatment, all soils can be processed.

This system, however, has the following disadvantages:

- A transportable unit for use in treating soil would be difficult to design.

- Many trays would be required to achieve energy efficiency.

Circulating Bed Combustor--

The circulating bed combustor was developed for the combustion of high-sulfur fuel to produce steam. It was developed as a modification of the bubbling fluidized bed combustor to achieve substantially higher system volumetric efficiencies. The technology should be applicable, given certain modifications, to stripping VOCs from soil with a gas. The technology would be applicable to free flowing feedstocks (sand or silt).

The incoming gas is preheated sufficiently to heat the soil to the required temperature. The hot gas is passed through a distributor at a velocity sufficient to entrain the soil. Contaminated soil is added above the distributor, entrained, and heated by the hot gases. The entrained soil is separated from the hot flue gases in a cyclone and recirculated into the bed. A solids draw-off from the cyclone maintains the material balance in the system. High clay soils would require significant premixing with sand before feeding to avoid agglomeration in the bed.

The major advantage of this process is its very high volumetric efficiency. Its major disadvantage is that it is limited to free flowing feedstocks.

Bubbling Bed Combustor--

A bubbling bed is made of a granular material (sandy soil) through which a gas is blown from a distributor at the bottom of the bed. The gas rate is controlled so that the bed material bubbles just to the point of incipient fluidization, but not sufficiently to lift solids from the bed. This technology can be used to remove VOCs from sandy soil by preheating the gas sufficiently to raise the temperature of the bed material so that the VOCs adsorbed on the solids are vaporized. The contaminated soil, which becomes the bed material, is fed in at the top of the bed and is withdrawn from the bottom. The gas leaving the top of the bed is withdrawn from the freeboard above the bed and appropriately treated before venting it to the atmosphere.

The residence time can be controlled by bed height or soil feedrate. The bed temperature is controlled by the temperature of the gas entering the bed. The advantage of this technology is the lower energy required for gas circulation. The major disadvantage is that it is limited to free-flowing feedstocks. High clay soils would require significant premixing with sand before feeding to avoid agglomeration in the bed.

Procedures for Contaminant Removal from Soil

Volatile Organic Compounds--

Process Parameters--

- Heat--Although very little testing has been done in this area, the soil will have to be heated if VOCs are to be removed to acceptable levels by gas stripping. The soil will need to be heated to between 100° and 400°C, depending upon the vapor pressure of the VOCs to be removed and the adsorptive forces binding the organic molecule to the soil particle. The addition of recuperative heat exchangers will reduce the amount of fuel required.

- Stripping Gas--Gas flow can be accomplished by blowing the air through or over the soil under pressure or by using an induced-draft fan to pull the gas through the soil under a vacuum. Any gas may be used as the stripping agent. Practical considerations tend to limit the choice to air or steam. Which should be chosen will depend on the type of soil to be treated, the type of VOC to be removed, the site location, and the objectives of the procedure.

- Post-treatment--Stripping of VOCs from soil with a gas at relatively low temperatures will produce a gas stream containing VOCs that must be removed or destroyed before the gas can be vented to the atmosphere. Removal of a condensible from a noncondensible by condensation is difficult and inefficient. For this reason, if the stripping agent is a gas such as air, removal and concentration of the VOCs by adsorption, or destruction by after-burning, would probably be required in many cases. However, if the stripping medium is a condensible such as steam, condensation followed by an appropriate treatment procedure such as gravity separation, biological oxidation or adsorption, or a combination, would be possible. There are four air gas treatment options: a secondary combustion chamber, catalytic oxidation, gas scrubbing, and adsorption.

- Soil Preparation--Some form of feed pretreatment is required. Pretreatment may be merely prescreening to remove the large material such as boulders and logs. It is reasonable to assume that almost all soils will contain fines that will be entrained in the gas. Provision must be made for the removal and adequate handling of these fines. Consideration must be given to the possibility that the VOCs may well be readsorbed on the surface of the fines if the gas is allowed to cool before the fines are removed.

- Soil Type--Silts and clays provide much more surface area per unit mass than sand and rock. In addition to a higher external surface area, some of this material may be porous, providing additional area and pores for adsorbing the VOC molecules. The wide range in particle size and density of most soils will provide severe problems for most stripping technologies and may well rule out the use of some. Soil high in clay will be particularly difficult to treat. Special provisions to prevent agglomeration in the bed will be required.

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Appendix. Priority Pollutants and Acutely Hazardous Substances*

Material	Hydro-philic	Hydro-phobic	Volatile	Metal
Volatiles				
acrolein	yes	no	yes	no
acrylonitrile	yes	no	yes	no
benzene	no	yes	yes	no
bromoform	no	yes	yes	no
carbon tetrachloride	no	yes	yes	no
chlorobenzene	no	yes	yes	no
chlorodibromomethane	no	yes	yes	no
chloroform	no	no	yes	no
dichlorobromomethane	no	no	yes	no
1,1-dichloroethane	no	no	yes	no
1,2-dichloroethane	no	no	yes	no
1,1-dichloroethylene	no	no	yes	no
1,2-dichloropropane	no	yes	yes	no
1,3-dichloropropylene	no	no	yes	no
ethylbenzene	no	yes	yes	no
methyl bromide	no	no	yes	no
methyl chloride	yes	no	yes	no
methylene chloride	yes	no	yes	no
tetrachloroethylene	no	yes	yes	no
toluene	no	yes	yes	no
1,2-dichloroethylene	no	no	yes	no
1,1,1-trichloroethane	no	yes	yes	no
1,1,2-trichloroethane	no	yes	yes	no
trichloroethylene	no	yes	yes	no
vinyl chloride	no	no	yes	no
Acid Extractables				
2-chlorophenol	yes	yes	no	no
2,4-dichlorophenol	no	yes	no	no
2,4-dimethylphenol	yes	yes	no	no
4,6-dinitrocresol	no	yes	no	no
2,4-dinitrophenol	no	yes	no	no
p-chloro m-cresol	no	yes	no	no
2-nitrophenol	no	no	no	no
pentachlorophenol	no	yes	no	no
phenol	yes	no	no	no
2,4,6-trichlorophenol	no	yes	no	no
Base - Neutral Extractables				
acenaphthene	no	yes	no	no
acenaphthylene	no	yes	no	no

(continued)

Appendix (continued).

Material	Hydro-philic	Hydro-phobic	Volatile	Metal
anthracene	no	yes	no	no
benzidine	no	no	no	no
benzo(a)anthracene	no	yes	no	no
benzo(a)pyrene	no	yes	no	no
3,4-benzofluoranthene	no	yes	no	no
benzo(ghi)perylene	no	yes	no	no
benzo(k)fluoranthene	no	yes	no	no
dichloroethoxymethane	yes	no	no	no
bis(2-chloroethyl)ether	yes	no	no	no
dichloroisopropyl ether	no	yes	no	no
diethylhexyl phthalate	no	yes	no	no
4-bromophenyl phenyl ether	no	yes	no	no
butylbenzyl phthalate	no	yes	no	no
2-chloronaphthalene	no	yes	no	no
4-chlorophenyl phenyl ether	no	yes	no	no
chrysene	no	yes	no	no
dibenzo(a,h)anthracene	no	yes	no	no
1,2 dichlorobenzene	no	yes	yes	no
1,3 dichlorobenzene	no	yes	no	no
1,4 dichlorobenzene	no	yes	no	no
3,3'dichlorobenzidene	no	yes	no	no
diethyl phthalate	no	yes	no	no
dimethyl phthalate	no	yes	no	no
di-n-butyl phthalate	no	yes	no	no
2,4-dinitrotoluene	no	yes	yes	no
2,6-dinitrotoluene	no	yes	yes	no
di-n-octyl phthalate	no	yes	no	no
1,2-diphenylhydrazine	no	yes	no	no
fluoranthene	no	yes	no	no
fluorene	no	yes	no	no
hexachlorobenzene	no	yes	no	no
hexachlorobutadiene	no	yes	no	no
hexachlorocyclopentadiene	no	yes	no	no
hexachlorethane	no	yes	no	no
indeno(1,2,3-cd)pyrene	no	yes	no	no
isophorone	yes	no	no	no
naphthalene	no	yes	no	no
nitrobenzene	no	no	no	no
N-nitrosodimethylamine	yes	no	yes	no
N-nitrosodiphenylamine	no	yes	no	no
N-nitrosodipropylamine	no	no	no	no
phenanthrene	no	yes	no	no
pyrene	no	yes	no	no
1,2,4-trichlorobenzene	no	yes	no	no

(continued)

Appendix (continued)

Material	Hydro-philic	Hydro-phobic	Volatile	Metal
Pesticides				
aldrin	no	yes	no	no
alpha BHC	no	yes	no	no
beta BHC	no	yes	no	no
gamma BHC	no	yes	no	no
delta BHC	no	yes	no	no
chlordane	no	yes	no	no
4,4'-DDT	no	yes	no	no
4,4'-DDE	no	yes	no	no
4,4'-DDD	no	yes	no	no
dieldrin	no	yes	no	no
alpha endosulfan	no	yes	no	no
beta endosulfan	no	yes	no	no
endosulfan sulfate	no	yes	no	no
endrin	no	yes	no	no
endrin aldehyde	no	yes	no	no
heptachlor	no	yes	no	no
heptachlor epoxide	no	yes	no	no
PCBs	no	yes	no	no
toxaphene	no	yes	no	no
Metals				
antimony	yes	no	no	yes
arsenic	yes	no	no	yes
beryllium	yes	no	no	no
cadmium	yes	no	no	yes
chromium	yes	no	no	yes
copper	yes	no	no	yes
lead	yes	no	no	yes
mercury	yes	no	no	yes
nickel	yes	no	no	yes
selenium	yes	no	no	no
silver	yes	no	no	yes
thallium	yes	no	no	yes
zinc	yes	no	no	yes
cyanide	yes	no	no	no
asbestos	no	no	no	no
Acutely Hazardous Materials				
acetaldehyde	yes	no	yes	no
allyl alcohol	yes	no	yes	no
allyl chloride	no	yes	yes	no
amyl acetate	yes	yes	yes	no
aniline	yes	yes	no	no
benzonitrile	no	yes	no	no

(continued)

Appendix (continued)

Material	Hydrophilic	Hydrophobic	Volatile	Metal
benzyl chloride	no	yes	yes	no
butyl acetate	yes	yes	yes	no
butylamine	yes	no	yes	no
captan	no	no	no	no
carbaryl	no	yes	no	no
carbofuran	no	yes	no	no
carbon disulfide	no	no	yes	no
chlorpyrifos	no	yes	no	no
coumaphos	no	yes	no	no
cresol	no	yes	no	no
crotonaldehyde	yes	no	yes	no
cyclohexane	no	yes	yes	no
2,4-D	no	yes	no	no
diazinon	no	yes	no	no
dicamba				
dichlobenil	no	yes	no	no
dichlone	no	yes	no	no
2,2-dichloropropionic	yes	no	no	no
dichlorvos	yes	yes	no	no
diethyl amine	yes	no	yes	no
dimethyl amine	yes	no	yes	no
dinitrobenzene	no	no	no	no
diquat	yes	no	no	no
disulfoton	no	no	no	no
diuron	no	yes	no	no
epichlorohydrin	yes	yes	yes	no
ethion	yes	yes	no	no
ethylene diamine	yes	no	yes	no
ethylene dibromide	no	yes	yes	no
formaldehyde	yes	no	yes	no
furfural	yes	no	no	no
guthion	no	yes	no	no
isoprene	no	yes	yes	no
isopropanolamine DBS	yes	yes	no	no
kelthane				
kepone	yes	yes	no	no
malathion	no	yes	no	no
mercaptodimethur				
methoxychlor	no	yes	no	no
methyl mercaptan	no	yes	yes	no
methyl methacrylate	no	yes	yes	no
methyl parathion	no	yes	no	no
mevinphos	yes	yes	yes	no
mexacarbate	no	yes	no	no
monoethyl amine	yes	no	yes	no
monomethyl amine	yes	no	yes	no

(continued)

Appendix (continued)

Material	Hydro-philic	Hydro-phobic	Volatile	Metal
naled				
naphthenic acid				
nitrotoluene	no	yes	no	no
parathion	no	yes	no	no
phenolsulfate				
phosgene	no	no	yes	no
propargite	yes	no	yes	no
propylene oxide	yes	no	yes	no
pyrethrins	no	yes	no	no
quinoline	yes	yes	no	no
resorcinol	yes	no	no	no
strontium	yes	no	no	yes
strychnine	no	yes	no	no
styrene	no	yes	no	no
2,4,5-T	no	yes	no	no
TDE				
2,4,5-TP				
trichlorofon				
triethanolamine DBS				
triethyl amine	yes	no	yes	no
trimethyl amine	no	yes	yes	no
uranium	yes	no	no	yes
vanadium	yes	no	no	yes
vinyl acetate	yes	yes	yes	no
xylene	no	yes	yes	no
xylenol	yes	yes	no	no
zirconium	yes	no	no	yes

*Source: CFR 40 Parts 122.21